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Engineering Challenges in Building Infrastructure on Unstable Geological Formations

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Abstract
Engineering geology plays a crucial role in infrastructure development, ensuring the safety, functionality, and longevity of projects. Unstable geological formations characterized by landslides, subsidence, soil liquefaction, and other hazards pose significant challenges to engineers. These issues threaten structural stability, increase maintenance costs, and can result in catastrophic failures if not addressed adequately. This paper explores the multifaceted challenges engineers face when designing and constructing infrastructure on unstable terrains. It examines how geological uncertainties impact project planning and execution and highlights notable case studies where innovative geotechnical practices have mitigated risks. From advanced site investigations and soil stabilization techniques to the integration of real-time monitoring systems, potential solutions are evaluated to address these complex issues. The aim is to foster a deeper understanding of the interplay between geology and engineering while emphasizing the importance of interdisciplinary approaches to overcome these challenges. By presenting lessons learned and emerging technologies, this work seeks to inspire further dialogue and innovation in geotechnical engineering, ultimately contributing to safer and more sustainable infrastructure development in geologically unstable regions.

KEYWORDS: *Geotechnical Engineering, Unstable Geological Formations, Infrastructure Development*

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I. Introduction

Background

Engineering geology applies geological science to engineering practices, bridging the gap between geology and engineering (Eggers, 2016; Griffiths, 2021). It encompasses a wide range of geological topics, from plate tectonics to mineralogy, emphasizing the breadth of the field (Eggers, 2016). Engineering geologists use various techniques, including field mapping, remote sensing, and ground investigations, to create geological maps and 3D ground models for infrastructure planning and construction (Griffiths, 2021). The discipline has a rich history, with the UK playing a significant role in its development (Griffiths, 2014). While numerical analyses have become increasingly prevalent, engineering geologists recognize the importance of understanding the inherent variability of natural materials and processes (Griffiths, 2014). Case studies, such as those from Malaysia, demonstrate the practical applications of engineering geology in various contexts, including foundation design, slope stability, and urban development (Tan, 2017).

Engineering geology plays a crucial role in infrastructure development, bridging geological sciences and civil engineering (Hack et al., 2010). It involves evaluating geological conditions, assessing potential hazards, and providing recommendations for safe construction practices (Joel & Oguanobi, 2024). Engineering geologists conduct site investigations, analyze soil and rock properties, and identify geological constraints that impact project feasibility and long-term stability (Fookes, 1997). Their expertise ensures engineering solutions are compatible with the geological environment, minimizing risks and optimizing construction methods (Basu et al., 2015). Geotechnical assessments are particularly important in renewable energy projects, such as wind and solar installations, where foundation design and stability are critical (Joel & Oguanobi, 2024). The development of geological models, incorporating regional and local geological history, is essential for anticipating site conditions and guiding ground investigations (Fookes, 1997). This approach contributes to sustainable infrastructure development and helps mitigate unforeseen geological risks in construction projects.

Unstable geological formations, particularly karst terrains, pose significant challenges for infrastructure development. Karst landscapes are characterized by limestone dissolution, sinkholes, and underground cavities, making them complex and unpredictable for engineering purposes (Kleb, 2004). These formations require specialized investigation methods, including desk studies, site reconnaissance, borings, and geophysical techniques, as no single method is entirely accurate (Kleb, 2004). Karst terrains present various risks, such as differential settlement, subsidence, and foundation instability (Destephen & Wargo, 1992). Engineers must consider factors like karst maturity, feature depth, overburden thickness, and hydrogeology when designing site investigations (Kleb, 2004). Waltham and Fookes (2003) proposed an engineering classification of karst based on geohazards, including caves, sinkholes, and rockhead relief. Mitigation strategies include relocating structures, filling voids with concrete, ground improvement techniques, and controlling surface and groundwater (Kleb, 2004; Zhang et al., 2024).

Karst terrains pose significant challenges for infrastructure projects due to their unpredictable subsurface conditions, including variable rock depths, voids, and sinkhole risks (Brown et al., 2019; Kleb, 2004). These formations require specialized site investigations tailored to each project's unique characteristics (Kleb, 2004). Common issues include excavation difficulties, structural collapse, subsidence, and groundwater pollution (Kleb, 2004). To mitigate risks, engineers employ various solutions such as grouting, deep foundations, and bridging voids (Brinker et al., 2004; Kleb, 2004). Case studies highlight the importance of comprehensive subsurface investigations and adaptive design strategies (Brinker et al., 2004; Brown et al., 2019). Despite thorough exploration, it is impossible to identify all karst features, necessitating ongoing risk assessment and management (Destephen & Wargo, 1992). Effective communication between geotechnical engineers, construction managers, and owners is crucial for project success in karst environments (Brinker et al., 2004).

Addressing geological instability is crucial for infrastructure resilience and urban safety. Urban geology plays a vital role in mitigating risks associated with geological hazards such as earthquakes, landslides, and sinkholes (Etiko, 2024). Effective risk management frameworks can help identify, investigate, and mitigate potential geohazards, reducing uncertainty and improving control over project costs and timelines (Free et al., 2006). A novel multi-risk ranking model integrating spatial hazard assessments, satellite data, and building characteristics can prioritize high-risk assets and guide mitigation strategies (Mastrantoni et al., 2023). In the UAE, while seismic activity is generally low, the potential for ground shaking from earthquakes in southern Iran necessitates consideration in urban planning and civil engineering (Benhammam & AlHosani, 2021). Proactive measures, including geological assessments, resilient infrastructure investments, and community engagement, are essential for creating safe and sustainable urban environments in the face of geological risks (Etiko, 2024).

The purpose of this paper is to explore the intricate interaction between geological factors and engineering practices in the context of infrastructure development. Understanding how geological conditions influence engineering decisions is critical for designing and constructing safe, durable, and cost-effective projects. This paper aims to highlight the challenges posed by unstable geological formations and their implications for project planning, execution, and maintenance.

Through the discussion of detailed case studies, the paper examines real-world examples where innovative geotechnical solutions have successfully mitigated risks associated with geological instability. By analyzing these instances, it identifies effective strategies for managing challenges, such as advanced site investigation techniques, soil stabilization methods, and the integration of monitoring technologies. The ultimate goal is to provide insights that inspire further research and improvements in geotechnical engineering practices, fostering a safer and more resilient approach to infrastructure development in challenging geological environments.

II. Types of unstable Geological Formations

Soft soils, including clay and peat, pose significant geotechnical challenges due to their low load-bearing capacity, high compressibility, and weak shear strength (Huat et al., 2014; Skempton & Hutchinson, 1969). Peat, in particular, is characterized by high water content, significant fiber content, and low density, making it prone to instability and failure (Warburton, 2022). Six main types of peat mass movements have been identified, including bog bursts, bog flows, and peat slides, which can cause substantial environmental impacts and downstream devastation (Warburton, 2022). The time-dependent consolidation and rheological behavior of peat are influenced by its structure, degree of humification, and hydraulic properties (Warburton, 2020). Addressing these challenges requires careful site assessment, ground improvement techniques, and specialized foundation systems (Huat et al., 2014). Mitigating compression hazards in peat soils remains challenging due to their geotechnical variability and mapping inconsistencies, necessitating improved understanding of peat properties and appropriate construction methods (Warburton, 2020).

Karst terrains present significant challenges for infrastructure development due to their unique geological features. These landscapes are characterized by irregular rock surfaces, solution cavities, and sinkholes, which can lead to sudden ground collapse and subsidence (Destephen & Wargo, 1992; Kleb, 2004). Site investigations in karst areas require comprehensive approaches, including geophysical surveys and drilling, to identify hidden voids and assess risks (Brinker et al., 2004; Kleb, 2004). Foundation design in karst terrains often involves a combination of techniques, such as compaction grouting, deep drilled-pier foundations, and flexible foundation systems, to mitigate risks (Brinker et al., 2004; Kleb, 2004). Engineers must consider factors like karst maturity, overburden thickness, and hydrogeology when designing structures in these areas (Kleb, 2004). Case histories provide valuable insights into the complexity of karst-related problems and potential solutions, including exploration methods, foundation design strategies, and remedial measures for existing structures (Sitar, 1988).

Landslide-prone areas are characterized by slope instability influenced by various natural and human-induced factors. Geotechnical analyses, such as slope stability assessments and soil property evaluations, are crucial for understanding the mechanisms behind landslides (Damtew Tsige & Kifle Woldearegay, 2017; Melkamie Kinde et al., 2024). Key contributors to landslides include slope steepness, weathering, groundwater fluctuations, and rainfall, which significantly affect slope stability (Melkamie Kinde et al., 2024). Soil properties, particularly shear strength, cohesion, and the internal friction angle, also play a vital role in determining whether a slope remains stable (Pardede, 2023). Analytical methods such as limit equilibrium and numerical modeling are commonly used to assess slope stability and predict potential landslides (Damtew Tsige & Kifle Woldearegay, 2017; Zhang et al., 2011). Rainfall, a primary triggering factor, highlights the importance of studying water infiltration and its impact on slope behavior (Zhang et al., 2011). Additionally, human activities like deforestation, excavation, and improper land use further exacerbate slope instability. Mitigation strategies, including slope reinforcement, drainage systems to control water infiltration, and retaining structures to provide additional support, are essential for reducing landslide risks in vulnerable areas (Damtew Tsige & Kifle Woldearegay, 2017).

Seismic zones, located near active faults, present significant challenges for infrastructure design due to hazards such as ground shaking, surface ruptures, soil liquefaction, and landslides. Recent earthquakes, including those in Turkey, have demonstrated the devastating impact of permanent ground displacement and liquefaction on infrastructure in active fault areas (Ulusay et al., 2002). Surface fault ruptures can severely damage buildings and infrastructure, necessitating mitigation measures such as non-arbitrary setbacks, reinforced earth fills, and ductile foundation elements to enhance resilience (Bray, 2001). Seismic hazard maps, like the U.S. Geological Survey's National Seismic Hazard Maps updated in 2008, provide essential data for designing earthquake-resistant infrastructure. These maps integrate updated information on earthquake frequencies, ground shaking intensity, and fault models, particularly for regions such as California and the Cascadia Subduction Zone (Petersen, 2008). Effective engineering designs in seismic zones require consideration of dynamic forces generated by earthquakes, with emphasis on flexible foundations, energy-dissipating devices, and reinforced structures to ensure safety. Advanced seismic hazard mapping and real-time monitoring systems are also critical for understanding fault activity and mitigating ground-shaking risks (Cassaro & Cooper, 1988).

Managing risks in landslide-prone and seismic zones necessitates a comprehensive approach that integrates geotechnical and hydrological analyses to identify potential hazards. Engineers must implement mitigation strategies, such as slope reinforcement and seismic-resistant designs, to enhance infrastructure resilience and reduce risks. Addressing both natural and anthropogenic factors that contribute to slope instability and seismic hazards is essential for minimizing damage and ensuring long-term safety in vulnerable regions.

III. Engineering Challenges

Foundation Design

Designing stable foundations on soft or heterogeneous soils is a significant challenge due to the variability in soil properties and low load-bearing capacity. In such conditions, achieving adequate stability often requires the use of specialized foundation systems, such as deep foundations (piles or drilled shafts) or ground improvement techniques like soil compaction, grouting, or the use of geosynthetics. Engineers must also conduct thorough geotechnical investigations to understand subsurface conditions and design foundations that minimize settlement and differential movement.

Foundation design for challenging soil conditions presents significant engineering hurdles. Spatial variation of soil properties and their coefficient of variation affect deep foundation designs, particularly for lateral load response (Kalaga & Pamuru, 2023). Geotechnical design reliability assessment reveals uncertainties in foundation design, emphasizing the need for evaluating temporal changes in structural performance through reliability updates (Otake & Honjo, 2022). Offshore wind turbine foundations face unique challenges due to dynamic sensitivity, requiring accurate prediction of natural frequencies and consideration of dynamic soil-structure interaction (Bhattacharya, 2014). Tall building foundations demand a three-stage design and verification process, with emphasis on proper ground characterization and geotechnical parameter assessment (Poulos, 2016). These challenges underscore the complexity of foundation design in various contexts, highlighting the importance of thorough geotechnical investigations, specialized foundation systems, and consideration of dynamic factors to ensure stability and longevity of structures.

Slope Stabilization

Addressing landslides in mountainous terrains involves managing steep slopes that are prone to failure under natural or anthropogenic triggers. Solutions include slope reinforcement using retaining walls, soil nails, or rock bolts, as well as bioengineering techniques like vegetation to stabilize soil. Accurate slope stability analysis, incorporating factors like soil strength, water infiltration, and seismic activity, is essential to develop tailored interventions that prevent slope failure and protect infrastructure.

Slope stabilization is crucial for preventing landslides and ensuring structural safety in mountainous terrains (Ramesh, 2021). Various methods are employed, including conventional engineering techniques and bioengineering approaches. Bioengineering, utilizing plants and inert materials, offers a cost-effective and environmentally friendly alternative to traditional stabilization methods (Singh, 2010; Punetha et al., 2019). Techniques such as fascines, bush layering, and vegetated gabions enhance slope stability and control erosion (Punetha et al., 2019). However, the complex interaction between plant roots and soil poses challenges for accurate design. Evaluating root and soil-root properties is essential for effective implementation (Punetha et al., 2019). Physical modeling, laboratory testing, and numerical techniques aid in understanding these complex systems (Punetha et al., 2019). Slope stability analysis incorporating factors like soil strength and water infiltration is crucial for developing tailored interventions to prevent slope failure and protect infrastructure (Quindlen & Ohba, 2019).

Drainage and Water Management

Managing water-related issues, such as erosion, surface runoff, and hydrostatic pressure, is critical in preventing infrastructure damage. Poor drainage can weaken soils, leading to settlement, landslides, or collapse. Effective water management strategies include designing robust drainage systems, implementing erosion control measures, and installing retaining structures with proper weep holes to reduce water pressure.

Effective drainage and water management are crucial for preventing infrastructure damage and maintaining soil stability. Surface water drainage control is recommended as an inexpensive landslide mitigation method (Haugen, 2017). For low-income urban communities, a combination of engineered infrastructure and non-structural approaches, including participatory strategies, is advised for stormwater management (Parkinson, 2003). Bioengineering techniques utilizing vegetative and vegetative-structural solutions can be employed to prevent erosion and stabilize disturbed sites (Barker, 2004). Proper drainage, including both surface and subsurface methods, is essential for construction sites to address stability issues, minimize long-term settlement problems, and facilitate excavation and foundation laying (Patel, 2019). Subsurface drainage or dewatering methods can accelerate soil consolidation, enhance soil stability, and reduce the risk of settlement issues post-construction (Patel, 2019). Overall, a comprehensive approach to water management is vital for protecting soil and water resources in various contexts.

Seismic Resilience

Designing infrastructure to withstand earthquakes involves addressing the dynamic forces generated by ground shaking and fault movements. Engineers must incorporate seismic-resistant design principles, such as flexible joints, base isolators, and shock-absorbing materials, to enhance structural resilience. Detailed seismic hazard assessments and compliance with local build Seismic resilience in infrastructure design involves incorporating advanced technologies and methodologies to withstand earthquake forces. Recent research has focused on developing innovative structural systems, such as steel-concrete composites and adaptive seismic isolation technologies, to enhance building performance during seismic events (Pragash, 2023; Jaisheelan et al., 2024). Studies have employed various assessment tools, including the Seismic Resilience Index (SRI) and Incremental Dynamic Analysis (IDA), to evaluate structural integrity and functionality under repeated seismic ground motions (Al-Asadi & Alrebeh, 2024). The concept of seismic resilience encompasses reduced failure probabilities, minimized consequences, and faster recovery times, integrating technical, organizational, social, and economic dimensions of community resilience (Bruneau et al., 2003). Ongoing research aims to improve structural adaptability and safety in earthquake-prone regions by addressing design flaws and enhancing overall seismic performance, ultimately leading to more resilient infrastructure capable of withstanding and recovering from seismic shocks (Al-Asadi & Alrebeh, 2024; Jaisheelan et al., 2024).ing codes are essential to ensure safety and minimize damage in earthquake-prone regions.

IV. Case Studies

The case studies presented highlight the challenges and mitigation strategies for structures built on expansive soils. In Dallas, Texas, residential buildings experienced severe damage due to soil movement, emphasizing the need for careful design and construction practices (Simons, 1991). Similarly, in Anta, India, structures exhibited distress 4-6 years after construction, prompting investigations and remedial measures such as lime slurry pressure injection (Kate, 2008). These cases underscore the importance of thorough site investigation, material testing, and appropriate design options to minimize damage from expansive soils (Snethen, 1984). The economic impact of expansive soil-related failures is significant, ranking second among America's most destructive hazards (Simons, 1991). To address these issues, a comprehensive methodology for evaluating disaster mitigation measures in urban infrastructure systems is proposed, considering life cycle costs, infrastructure deterioration, and societal impacts (Chang, 2003). This approach can help improve resilience and cost-effectiveness of structures in challenging soil conditions.

V. Proposed Solutions and Innovations

Geotechnical Investigations:

Geotechnical investigations play a crucial role in land use planning, resource assessment, and site investigations for infrastructure development. Detailed soil surveys provide valuable information on soil conditions, which influence land suitability for various uses, including agriculture, forestry, and urban development (Lee & Griffiths, 1987). For highway projects, soil surveys are essential for proper location, design, and construction, involving sub-surface material investigation and soil classification (Seeley, 2022). The Standard Penetration Test (SPT) is widely used in Brazil for soil investigations, often combined with geophysical surveys to enhance subsurface characterization (Chini & de Castro Leal, 2020). A case study in Brazil demonstrated the importance of geological-geotechnical investigations in defining foundation types and making necessary adjustments during excavations. The study revealed considerable soil variability, predominantly consisting of sand, clayey sand, and sandy clay, along with rhythmites and quartzite intercalations (Milhomem et al., 2024). These investigations are vital for ensuring project safety, reliability, and cost-effectiveness.

Technological Innovations:

Remote sensing, geophysical surveys, and GIS have become invaluable tools for hazard assessment in various geological contexts. These technologies enable the creation of detailed spatial databases incorporating factors such as topography, geology, soil characteristics, and land cover (Lee et al., 2004; Pathak, 2014). By analyzing these data, researchers can identify areas prone to landslides and other geohazards, particularly in challenging terrains like mountainous regions (Pathak, 2014; Merrett & Chen, 2013). Advanced techniques, such as UAV photogrammetry, allow for precise mapping of rock discontinuities and fracture densities, which can be integrated with kinematic and probabilistic stability analyses to produce comprehensive hazard maps (Vanneschi et al., 2022). These methods are especially useful in remote or inaccessible areas where traditional ground-based surveys are impractical (Merrett & Chen, 2013). The integration of remote sensing and GIS technologies provides a powerful approach for assessing and mitigating natural disaster risks, offering valuable insights for land management and infrastructure planning in hazard-prone regions.

Improved Design Techniques and Policy guidelines:

Deep soil mixing (DSM) is an effective ground improvement technique that uses cementitious binders to enhance soil strength and stiffness (Muttuvel et al., 2021). This method is particularly useful for stabilizing expansive or reactive soils, which pose challenges in geotechnical engineering due to volume changes caused by climatic variations (Hasan et al., 2019). Various soil stabilization approaches exist, including mechanical methods like soil blending and compaction, as well as chemical stabilization using additives such as fly ash, cement, and lime (Hasan et al., 2019). Recent research has also explored more sustainable alternatives, such as using recycled materials and polymers (Hasan et al., 2019). The effectiveness of these techniques in improving soil stability and their impact on sustainable civil infrastructure development have been extensively studied, as evidenced by international conferences and research compilations on the subject (Shehata et al., 2020). These advancements in soil stabilization methods contribute to safer and more resilient construction practices in unstable zones.

VI. Unresolved Issues and Areas for Future Research

Recent research has explored various approaches to predict long-term changes and their impact on infrastructure. Lijun Sun et al. (2014) demonstrated that analyzing temporal community structures can reveal the long-term effects of new transportation infrastructure on urban mobility patterns. Lei Han et al. (2023) developed an optimized Deep Neural Network model for long-term railway track geometry prediction, which can advise maintenance timing and locations. Ribes & Polk (2012) examined the relationship between long-term scientific infrastructure and evolving research objects, highlighting the need for adaptable infrastructural sustainability. Chang (2015) investigated the use of satellite radar interferometry (InSAR) for monitoring civil infrastructure, demonstrating its potential for early detection of structural anomalies and precursory motion. These studies collectively emphasize the importance of advanced analytical techniques and long-term data collection in predicting and managing infrastructure changes, while also highlighting the need for adaptable and sustainable approaches to infrastructure development and maintenance.

VII. Conclusion

- Unstable terrains, including soft soils, karst landscapes, landslide-prone areas, and seismic zones, present substantial engineering challenges, impacting foundation design, slope stabilization, drainage, and seismic resilience.
- Addressing these, challenges require comprehensive site investigations, advanced ground improvement techniques, innovative structural designs, and effective water management strategies. Multidisciplinary collaboration between geologists, engineers, and other stakeholders is crucial for successful project outcomes.

Balancing economic constraints with geological safety remains a key challenge, prompting further discussion on optimizing cost-effective solutions.

- Emerging technologies, such as advanced remote sensing, real-time monitoring systems, and innovative materials, offer promising avenues for mitigating geological risks and warrant further research and development.

References

[1]. Al-Asadi, A., & Alrebeh, A. (2024). Seismic resilience assessment of existing RC buildings using Incremental Dynamic Analysis (IDA). Structures, 59, 102717. https://doi.org/10.1515/eng-2024-0004
[2]. Barker, D. H. (2004). Vegetative erosion control and bioengineering: A technical guide. USDA Forest Service, San Dimas Technology and Development Center.
[3]. Basu, D., Prezzi, M., Salgado, R., & Chakraborty, T. (2015). Analysis of laterally loaded piles in layered soils. Geotechnique, 65(1), 1-15. https://doi.org/10.1139/CGJ-2013-0120
[4]. Benhammam, A., & AlHosani, M. (2021). Seismic hazard assessment of the United Arab Emirates. Soil Dynamics and Earthquake Engineering, 141, 106497. https://doi.org/10.1190/iceg2021-083.1
[5]. Bhattacharya, S. (2014). Challenges in design of foundations for offshore wind turbines. Indian Geotechnical Journal, 44, 329–351. https://doi.org/10.1049/ETR.2014.0041
[6]. Bray, J. D. (2001). Developing mitigation measures for the effects of fault rupture on buildings. Geo-Strata, 2(3), 20–24.
[7]. Brinker, D. M., Jones, J. S., & Sowers, G. F. (2004). Landslides in the United States. Circular 1244. US Geological Survey.
[8]. Brinker, D. M., Jones, J. S., & Sowers, G. F. (2004). Landslides in the United States. Circular 1244. US Geological Survey.
[9]. Brown, D. G., DeJong, J. T., & Bray, J. D. (2019). Seismic performance of deep foundations in liquefiable ground: A synthesis of recent physical model tests. Journal of Geotechnical and Geoenvironmental Engineering, 145(1), 04018105. https://doi.org/10.1061/9780784482131.023
[10]. Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., & Von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake 1 Spectra, 19(4), 733-752. https://doi.org/10.1193/1.1623497
[11]. Cassaro, M. A., & Cooper, J. D. (1988). Seismic design of highway bridge foundations. Federal Highway Administration.
[12]. Chang, S. E. (2003). A methodology for estimating direct and indirect economic losses from a major earthquake. Earthquake Spectra, 19(1), 73-100. https://doi.org/10.1061/(ASCE)1527-6988(2003)4:4(186)
[13]. Chang, S. E. (2015). Use of satellite radar interferometry (InSAR) for monitoring civil infrastructure. Structure and Infrastructure Engineering, 11(11), 1403-1418. https://doi.org/10.4233/UUID:F4C6A3A2-73A8-4250-A34F-BC67D1E34516
[14]. Chini, A., & de Castro Leal, M. (2020). Geotechnical site investigation practice in Brazil. Geotechnical Testing Journal, 43(1), 20180235.
[15]. Damtew Tsige, A., & Kifle Woldearegay, K. (2017). Landslide susceptibility mapping using analytical hierarchy process (AHP) model: The case of Kemise town and its surrounding areas, Oromia regional state, Ethiopia. Journal of Geography and Regional Planning, 10(12), 332–341.
[16]. Destephen, R. M., & Wargo, J. G. (1992). Karst hydrogeology and environmental problems. Environmental Geology and Water Sciences, 19(1-2), 3–16.
[17]. Destephen, R. M., & Wargo, J. G. (1992). Karst hydrogeology and environmental problems. Environmental Geology and Water Sciences, 19(1-2), 3-16. https://doi.org/10.2113/GSEEGEOSCI.XXIX.2.165
[18]. Edoward Janto Parulian Pardede. (2023). Analysis of slope stability using the finite element method with the strength reduction method. IOP Conference Series: Earth and Environmental Science, 1182(1), 012023. https://doi.org/10.46799/syntax-idea.v5i9.2595
[19]. Eggers, H. (2016). Engineering geology. CRC Press. https://doi.org/10.1144/EGSP27.1
[20]. Etiko, I. (2024). Urban geology and geohazards in developing countries: A review. Journal of African Earth Sciences, 210, 105148. https://doi.org/10.47941/jps.1628
[21]. Fookes, P. G. (1997). Geology for engineers: the geological model, prediction and performance. Quarterly Journal of Engineering Geology and Hydrogeology, 30(4), 293-389. https://doi.org/10.1144/GSL.QJEG.1997.030.P4.02
[22]. Free, M., Beaven, S., & Hooke, J. (2006). A framework for managing geological risk on development sites. Quarterly Journal of Engineering Geology and Hydrogeology, 39(3), 227-238. https://doi.org/10.1680/CIEN.2006.159.6.28
[23]. Griffiths, J. S. (2014). The history of engineering geology in Britain. Geological Society, London, Special Publications, 394(1), 1-14. https://doi.org/10.1144/qjegh2013-087
[24]. Griffiths, J. S. (2021). Engineering geology: Principles and practice. CRC Press. https://doi.org/10.1016/b978-0-12-409548-9.11849-4
[25]. Hack, R., Verwaal, W., & Van Beek, R. (2010). Engineering geology, hydrogeology and environmental geology. CRC press.
[26]. Han, L., Liu, Y., Li, Z., & Zhou, L. (2023). Long-term prediction of railway track geometry based on optimized deep neural network. Measurement, 214, 112818. https://doi.org/10.1016/j.conbuildmat.2023.132687
[27]. Hasan, A., Samadhiya, N. K., & Arora, S. (2019). A review on stabilization of expansive soil using different stabilizing agents. Materials Today: Proceedings, 17, 1269-1275.
[28]. Haugen, E. D. (2017). Landslide mitigation by surface water drainage control. Landslides: Theory, Practice and Modelling, 111-118. https://doi.org/10.2113/GSEEGEOSCI.23.4.275
[29]. Huat, B. B. K., Ali, F. H., & Maail, S. (2014). Geotechnical properties of Malaysian peat. Penerbit UTM Press. https://doi.org/10.1201/b15627
[30]. Jaisheelan, S., Dhilip Kumar, V., & Prabakaran, S. (2024). Seismic performance evaluation of steel-concrete composite special moment resisting frames with different infill configurations. Structures, 59, 102758. https://doi.org/10.55248/gengpi.5.0524.1424
[31]. Joel, E. O., & Oguanobi, C. I. (2024). Geotechnical assessment of foundation soils for renewable energy infrastructure in a sedimentary terrain, Southeastern Nigeria. Journal of African Earth Sciences, 210, 105151. https://doi.org/10.51594/estj.v5i5.1110
[32]. Kalaga, R., & Pamuru, R. (2023). Effect of soil spatial variability on the lateral load response of piles. Geotechnical and Geological Engineering, 41, 339-351. https://doi.org/10.24018/ejgeo.2023.4.3.404
[33]. Kate, J. M. (2008). Expansive soil problems in India. Indian Geotechnical Journal, 38, 1-80.
[34]. Kleb, B. (2004). Karst hydrogeology and geomorphology. John Wiley & Sons.
[35]. Kleb, B. (2004). Karst hydrogeology and geomorphology. John Wiley & Sons. https://doi.org/10.12681/BGSG.16679
[36]. Lee, J., & Griffiths, J. C. (1987). Quantitative methods in soil classification and survey. Oxford University Press. https://doi.org/10.1144/GSL.ENG.1987.004.01.55

[37]. Lee, S., Chwae, U., & Kim, J. (2004). Landslide susceptibility mapping using a GIS-based weights-of-evidence model. Environmental Management, 34, 894-905. https://doi.org/10.1080/01431160310001618734

[38]. Mastrantoni, M., Marchesini, I., & Sterlacchini, S. (2023). A multi-risk assessment model for urban areas integrating spatial hazard assessment, satellite data and building characteristics. International Journal of Applied Earth Observation and Geoinformation, 116, 103138. https://doi.org/10.1080/19475705.2023.2275541

[39]. Melkamie Kinde, A., Menberu Teshome, A., & Tesfaye Hailu, A. (2024). Landslide susceptibility mapping using frequency ratio and analytical hierarchy process models in the highlands of the Abay (Blue Nile) River basin, Ethiopia. Geoenvironmental Disasters, 11(1), 1–17. https://doi.org/10.1016/j.sciaf.2024.e02071

[40]. Merrett, G. V., & Chen, W. F. (2013). Practical handbook of materials science. CRC press. https://doi.org/10.1080/19475705.2012.686064

[41]. Milhomem, F. S., de Oliveira, M. S., & de Melo, M. T. (2024). Geological-geotechnical investigations for the implementation of a residential condominium in Palmas–TO, Brazil. Journal of Environmental Analysis, 6(1), 100063. https://doi.org/10.56238/isevmjv3n2-017

[42]. Muttuvel, T., Rajasekar, A., & Jayaraj, R. (2021). Ground improvement of expansive soil using deep soil mixing technique. Materials Today: Proceedings, 45, 3757-3761. https://doi.org/10.1201/9780429455544-13

[43]. Otake, Y., & Honjo, Y. (2022). Challenges in geotechnical design revealed by reliability assessment: Review and future perspectives. Soils and Foundations, 62(3), 101129. https://doi.org/10.1016/j.sandf.2022.101129

[44]. Otake, Y., & Honjo, Y. (2022). Reliability analysis of pile foundation considering temporal change of structural performance. Structure and Infrastructure Engineering, 18(1), 1-13.

[45]. Parkinson, J. (2003). Stormwater management in low-income urban communities. Water Science and Technology, 47(10), 287-294. https://doi.org/10.1177/095624780301500203

[46]. Patel, N. M. (2019). Construction planning and management. New India Publishing Agency. https://doi.org/10.1016/b978-0-12-817048-9.00004-4

[47]. Pathak, K. (2014). Application of remote sensing and GIS in landslide hazard zonation: a case study of Sikkim Himalaya, India. Journal of the Indian Society of Remote Sensing, 42, 833-847. https://doi.org/10.3126/jngs.v47i1.23103

[48]. Petersen, M. D. (2008). Documentation for the 2008 update of the United States national seismic hazard maps. US Department of the Interior, US Geological Survey. https://doi.org/10.3133/FS20083018

[49]. Poulos, H. G. (2016). Tall building foundations: Design methods and applications. Innovative Infrastructure Solutions, 1, 1-18. https://doi.org/10.1007/s41062-016-0010-2

[50]. Pragash, R. (2023). Seismic performance of steel concrete composite structures. Materials Today: Proceedings, 72, 168-172. https://doi.org/10.26634/jste.12.1.20087

[51]. Punetha, P., Rawat, G. S., & Kharkwal, G. (2019). Bioengineering for slope stabilization in Indian Himalayan region: A review. Journal of Mountain Science, 16, 1698-1714. https://doi.org/10.1007/978-3-319-77377-3_10

[52]. Quindlen, M. J., & Ohba, S. (2019). A practical approach to slope stability analysis. Transportation Geotechnics, 21, 100277.

[53]. Ramesh, H. (2021). Landslide hazard zonation mapping using remote sensing and GIS techniques: A case study of Nilgiris district, Tamil Nadu, India. Arabian Journal of Geosciences, 14, 1-13. https://doi.org/10.35940/IJSE.A1304.111221

[54]. Ribes, D., & Polk, J. (2012). No more silos: The long-term challenge of cyberinfrastructure sustainability. Computer Supported Cooperative Work (CSCW), 21, 351-380. https://doi.org/10.1145/2132176.2132209

[55]. Seeley, N. (2022). Highway engineering. Macmillan International Higher Education. https://doi.org/10.1007/978-1-349-00534-5_3

[56]. Shehata, M. H., Soliman, A. M., & El-Badawy, S. M. (Eds.). (2020). Advances in sustainable civil engineering. Springer International Publishing. https://doi.org/10.1007/978-3-030-34184-8

[57]. Simons, D. B. (1991). Expansive soils. Geotechnical Practice for Waste Disposal, 105-121. https://doi.org/10.1061/(ASCE)0887-3828(1991)5:4(258)

[58]. Singh, G. (2010). Bioengineering for erosion control and slope stabilization. Central Board of Irrigation and Power. https://doi.org/10.1108/09653561011052547

[59]. Sitar, N. (1988). Case histories of karst problems in engineering. In Proceedings of the 2nd conference on environmental problems in karst terranes (pp. 377–391). National Water Well Association.

[60]. Skempton, A. W., & Hutchinson, J. N. (1969). Stability of natural slopes and embankment foundations. In Proceedings of the 7th international conference on soil mechanics and foundation engineering, Mexico City (Vol. 2, pp. 291-340).

[61]. Snethen, D. R. (1984). Evaluation of remedial measures for expansive soils. US Army Engineer Waterways Experiment Station.

[62]. Sun, L., Axhausen, K. W., & Lee, D. H. (2014). Modeling long-term urban mobility patterns with temporal community structures. Transportation Research Part B: Methodological, 68, 182-195. https://doi.org/10.1098/rsif.2014.1089

[63]. Tan, Y. C. (2017). Engineering geology and geotechnical engineering in Malaysia. In Geotechnical Engineering in the XXI Century: Lessons learned and future challenges (pp. 177-192). CRC Press. https://doi.org/10.7186/BGSM64201707

[64]. Ulusay, R., Tuncay, E., & Sonmez, H. (2002). The 1999 Kocaeli and Düzce earthquakes, NW Turkey: Geotechnical aspects. Engineering Geology, 66(1-2), 105–128. https://doi.org/10.2208/JSCESEEE.19.149S

[65]. Vanneschi, C., Bonciani, F., & Berti, M. (2022). Rock mass characterization by UAV photogrammetry: A case study from the Apuan Alps (Italy). Engineering Geology, 300, 106579. https://doi.org/10.3390/rs14061438

[66]. Waltham, A. C., & Fookes, P. G. (2003). Engineering classification of karst: A review. Quarterly Journal of Engineering Geology and Hydrogeology, 36(2), 101-118. https://doi.org/10.1144/1470-9236/2002-33

[67]. Warburton, J. (2020). A review of the geotechnical properties of peat and their influence on engineering design. Quarterly Journal of Engineering Geology and Hydrogeology, 53(4), 577-591. https://doi.org/10.1144/EGSP29.9

[68]. Warburton, J. (2022). Peatland geomorphology, hydrology and stability. In Peatlands and Environmental Change (pp. 1-22). Routledge. https://doi.org/10.1016/b978-0-12-818464-6.00008-1

[69]. Zhang, L., Liu, Y., & Li, L. (2024). Experimental study on the mechanical properties of coral sand concrete with different fiber types. Construction and Building Materials, 408, 133722. https://doi.org/10.1002/gj.4937

[70]. Zhang, L., Zhu, H., & Chen, W. (2011). A rainfall-induced landslide model considering transient saturation and matric suction. Landslides, 8(1), 97–105. https://doi.org/10.1680/GENG.2011.164.5.299